DETECTION OF CREEP DAMAGE BY ULTRASONICS

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INTRODUCTION

Creep damage is known to affect the service life of fossil plant components. Nondestructive examination for the detection of such damage is important for assessing the remaining service life of the affected component. Ultrasonic methods have been investigated for use as inservice inspection tools in a project being funded by the Electric Power Research Institute (RP 1865-7). This on-going research has shown that the velocity of sound waves is altered by the material damage (cavitation at grain boundaries). The amount of change in the velocity can be correlated to the amount of damage. Other EPRI projects have developed a methodology to correlate the amount of cavitation to remaining service life of the material. Development of these ultrasonic methods will allow rapid performance of a volumetric examination during a short plant outage to detect the damage and estimate the remaining service life.

Creep may be found in such fossil plant equipment as steam lines, superheater tubes, and turbine components operating at high stresses and temperatures. While it may not be visibly apparent, creep can cause severe damage to the component. Creep often occurs in the form of cavities at grain boundaries that coalesce to form microcracks. This microstructural degradation reduces the fracture toughness of the material and may render the component unsafe for continual operation. In certain cases, a reduction in fracture toughness makes a flaw equal to the critical crack size that otherwise would have been noncritical in an unaffected material. Creep also is known to occur in the heat-affected zone of ferritic steels and austenitic steels.

In essence, creep cavitation will reduce the remaining life of a component. Work done by Central Electricity Research Laboratory and Electric Power Research Institute [1] demonstrated the relationship between creep cavitation and remaining life. An empirical formula that correlates this relationship was obtained from the ERA study as follows:

$$(1 - t/t_r) = 1 - (1 - A)^{n\lambda/(\lambda-1)} \qquad (1)$$

where A is number fraction of grain boundaries undergoing cavitation, t is operation life of material, t_r is total life of material, $(1-t/t_r)$ is remaining life fraction, and n and λ are two material constants.

If creep cavitation could be measured by some nondestructive evaluation (NDE) method, then it could be used to calculate the remaining life. One NDE method used for creep detection is surface replication [2,3]. With this approach, replicas of a polished surface are analyzed under either an optical or a scanning electron microscope. Fig. 1 shows creep cavities detected by replication. While replication can detect early stages of creep cavitation, the method has certain disadvantages. Replication is not volumetric, is limited to surfaces, and is a time-consuming process. Replication is not practical for examination of large areas of plant piping or steam headers.

The goal of this current project is to develop NDE methods that can be applied in fossil plants to detect creep [4,5] damage. The methods should be able to perform a volumetric inspection and be sufficiently fast so that several locations can be inspected during a single outage.

In the present study, ultrasonic methods were investigated to detect creep damage. Theoretical studies performed earlier [6,7] have shown that microcracks or cavities in a material will reduce the velocity of both longitudinal (L) and shear (S) waves. Temple (7) has predicted that the decrease in velocity of L-waves (v_L) would be more than that of S-waves (v_S). The relative changes in the velocity of L-waves and S-waves are caused by changes in the bulk modulus and shear modulus produced by microcracking [8].

ULTRASONIC TESTS

Creep Damage

Creep samples were tested to verify theoretical models. The samples were made from alpha-iron to avoid any effects of carbide inclusions on ultrasonic scattering. Future work on this project will be performed on low-alloy steel samples.

The test samples were machined to the shape shown in Fig. 2. The gauge length of the specimens was 37 mm (1.5 inch); width, 8.5 mm (0.34 inch); and thickness, 6.3 mm (0.25 inch). Twelve specimens were crept at 700°C (1292°F) in high-purity argon, in accordance with the previous work done by Cane and Gamewood [9]. Table 1 presents the values of approximate grain diameter, creep stress, creep time, and the strain experienced by each sample. After creep, all the samples were machined flat, and ultrasonic measurements were taken at the eleven points shown in Fig. 2. Ultrasonic tests included velocity measurements of longitudinal, shear, surface, and creeping waves. The L-wave velocity was measured at a frequency of 10 MHz and S-wave velocity was measured at 5 MHz.

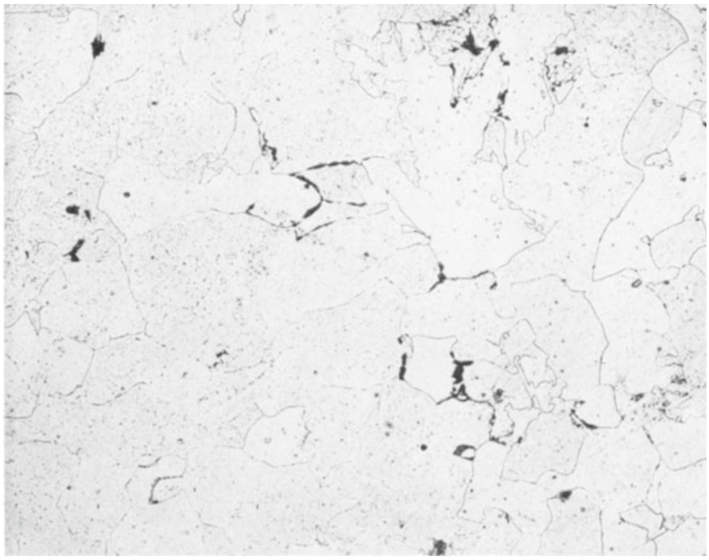

Fig. 1. Creep cavities (black spots on grain boundaries) detected by replication in a steam lead removed from service in a fossil plant. The replica-tion method is slow for field inspection and is limited to surface inspection (SwRI Micrograph No. 34097, Mag = 200X).

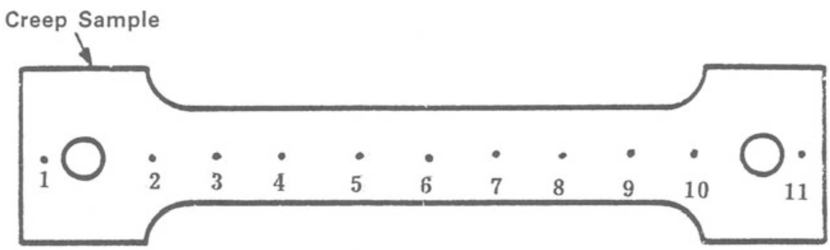

Fig. 2. Creep test sample. Ultrasonic measurements were taken at the eleven points. Points 2 through 10 are equally spaced by 1 cm (0.39 inch).

Ultrasonic L-wave and S-wave velocity measurements are shown in Table 2. These values correspond to the minimum velocity measured along the sample length relative to the nominal velocity at the end of the sample. The nominal velocity in each sample will depend somewhat on the microstructure. Results show that the L-wave velocity decreased by as much as 3.4 percent relative to sample A-20, and the S-wave velocity decreased by 1.9 percent in the crept region. This result is in direct agreement with the model of Temple [7], which predicted that the L-wave velocity would decrease more than the S-wave velocity. Typical plots of velocity along the length of the samples, given in Fig. 3, show that velocity is not uniform along the specimen length. This means that creep cavitation in these samples was not uniformly distributed and resulted in a nonuniform strain. Fracture will eventually occur at the point with

Table 1

TEST SAMPLE MATRIX WITH VALUES OF GRAIN DIAMETER, CREEP STRESS, CREEP TIME, AND CREEP STRAIN

Sample	Grain Size (μm)	Stress (MPa)	Time (Hrs)	Strain (percent)
A- 9+	200	17.4	24.9	24.6
A-13	200	17.4	14.7	8.1
A-14	200	17.4	19.7	7.5
A-17+	30	17.4	11.3	20.5
A-25	30	17.4	50.0	11.6
A-27+	30	17.4	59.6	26.6
A-28	30	17.4	35.0	7.1
A-18+	30	17.4	79.4	29.3
A-20	30	25.0	6.4	26.2
A-22+	30	25.0	8.0	30.1
A-16	30	25.0	5.0	12.8
A-23	30	25.0	6.0	21.2

+Specimen fracture during creep test

Table 2

ULTRASONIC LONGITUDINAL- AND SHEAR-WAVE VELOCITIES IN CREEP SAMPLES
(Error in velocity measurement is approximately 0.1 percent)

	Longitudinal Wave			Shear Wave		
Sample	End of Sample	Minimum Velocity	Percent Change	End of Sample	Minimum Velocity	Percent Change
A- 9+	5.94	5.71	-3.9	3.24	3.13	-3.4
A-13	5.93	5.93	0.0	3.23	3.24	+0.3
A-14	5.92	5.93	+0.2	3.24	3.25	+0.3
A-17+	5.93	5.75	-3.0	3.24	3.18	-1.8
A-25	5.92	5.79	-2.2	3.24	3.20	-1.2
A-27+	5.92	5.64	-4.7	3.24	3.17	-2.2
A-28	5.91	5.89	-0.5	3.24	3.23	-0.3
A-18+	5.92	5.70	-3.7	3.24	3.18	-1.8
A-20	5.92	5.72	-3.4	3.24	3.18	-1.8
A-22+	5.93	5.68	-4.2	3.25	3.17	-2.5
A-16	5.91	5.89	-0.3	3.24	3.23	-0.3
A-23	5.91	5.85	-1.0	3.24	3.22	-0.6

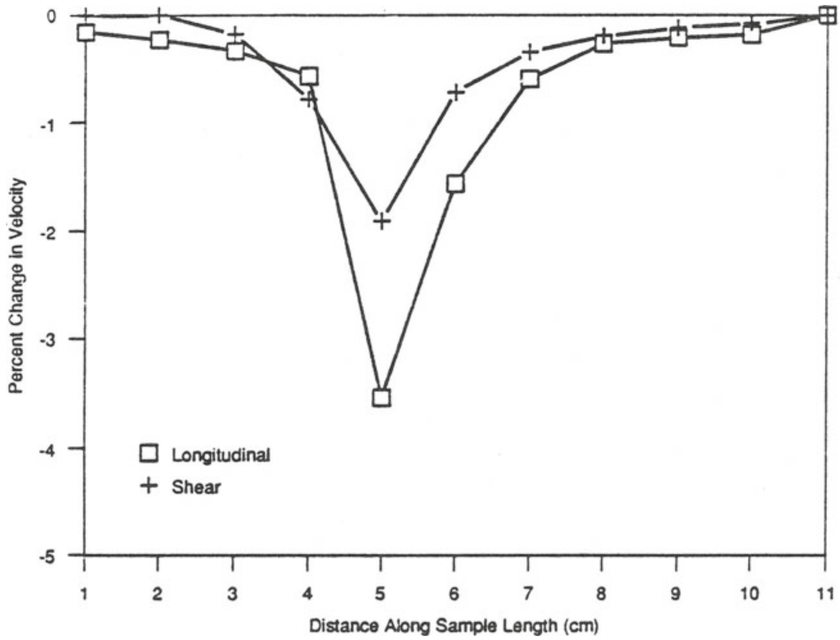

Fig. 3. L-wave and S-wave velocity along the sample length (see Fig. 2). L-wave velocity decreased by as much as 3.4 percent on Sample A-20.

minimum velocity, which should coincide with the location of maximum creep.

Surface-wave measurements were taken in the through-transmission mode using two 10-MHz transducers placed on the surface of the specimen and separated by 18 mm (0.7 inch). Measurements were taken at several locations along the length of the specimen, and the minimum value recorded in Table 3. Because of this configuration, the measurements could not be taken close to the fracture surface on the samples that failed during creep tests. Thus, the minimum velocity which would be next to the fracture surface could not be measured. The results of the measurements are summarized in Table 3, and a typical plot of velocity is shown in Fig. 4. The results show a general decrease in the measured velocity. The surface wave method is very sensitive to creep close to the component surface.

Creeping waves were also investigated. They are produced by 90-degree refracted L-waves at a frequency of 5 MHz. These waves have two advantages over surface waves. First, they are expected to penetrate deeper in the metal to about 5 mm (0.2 inch) (10). Second, the percentage of decrease in velocity is expected to be more for creeping waves than for surface waves because creeping waves are converted from L-waves, and surface waves are converted from S-waves. Results of creeping-wave velocity measurements showed this to be true (see Table 3). A representative plot of velocity variation along the sample is shown in Fig. 4. In general, the ultrasonic velocity measurements were very encouraging. A decrease in ultrasonic velocity was observed for all four types of wave modes. The application of a specific wave mode for creep detection will depend on the geometry of the part and the expected location of creep damage. Surface waves and creeping waves should be applied when the

Table 3

CREEPING- AND SURFACE-WAVE VELOCITIES IN CREEP SAMPLES
(Error in velocity measurement is approximately 0.1 percent)

	Creeping Wave			Surface Wave		
Sample	End of Sample	Minimum Velocity	Percent Change	End of Sample	Minimum Velocity	Percent Change
A- 9+	5.90	5.56	-5.8	3.17	3.05	-3.8
A-13	5.91	5.90	-0.2	3.17	3.16	-0.3
A-14	5.90	5.89	-0.2	3.17	3.16	-0.3
A-17+	5.90	5.74	-2.7	3.18	3.15	-0.9
A-25	5.90	5.62	-4.7	3.19	3.13	-1.9
A-27+	5.90	5.76	-2.4	3.19	3.14	-1.6
A-28	5.90	5.89	-0.2	3.19	3.18	-0.3
A-18+	5.90	5.72	-3.0	3.19	3.15	-1.2
A-20	5.90	5.70	-3.4	3.18	3.11	-2.2
A-22+	5.91	5.80	-1.9	3.18	3.16	-0.6
A-16	5.90	5.89	-0.2	3.19	3.19	0.0
A-23	5.90	5.78	-2.0	3.18	3.14	-1.2

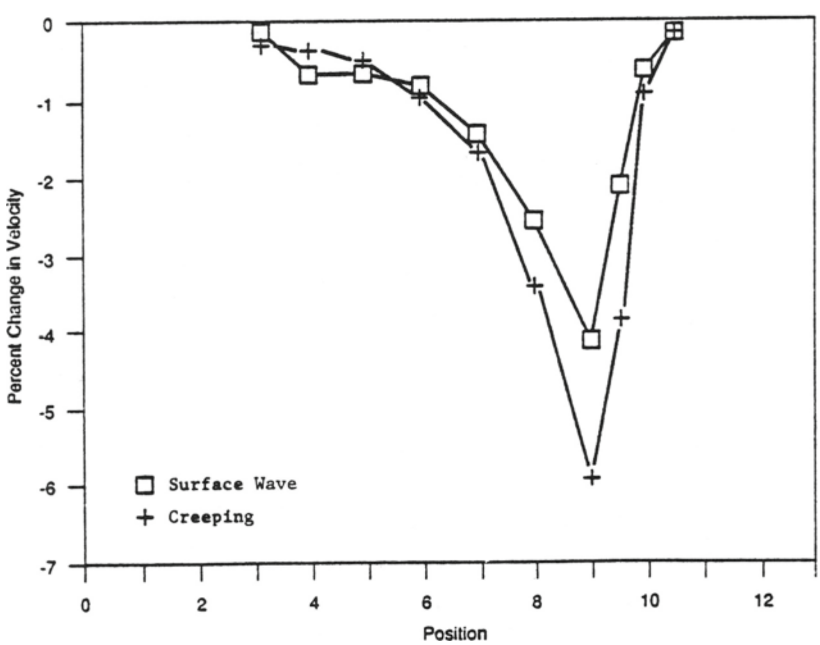

Fig. 4. Surface-wave and creeping-wave velocity measurements in sample A-9

damage is localized close to the surface. Surface and creeping wave velocities are generally easier to measure, since calculation for velocity does not require knowledge of the thickness of the material under test. The thickness of the material must be known for L- and S-wave velocity measurement. L- and S-waves would be more applicable for bulk damage across the specimen thickness.

A qualitative relationship between creep damage and decrease in ultrasonic velocities was also obtained. Fig. 5 shows a plot of the decrease in the longitudinal- and shear-wave velocities versus creep strain in each sample. The figure shows a general decrease in velocity with incresed creep strain with the L-wave decreasing more than the S-wave velocity. Such a relationship is important when assessing the amount of creep damage in the material and can be used to predict the amount of damage. Fig. 5 shows a general decrease in velocity with a large scatter in the data. The large scatter is produced because we are correlating the minimum velocity at a single point in the specimen to the average strain in the specimen. A better correlation would be expected if the velocity measured at a specific point is plotted against the grain boundary or cavitation at that point. Such an analysis will require a detailed metallurgical analysis requiring the measurement of cavitation, microcracking, and percent grains undergoing cavitation. Such investigations have not yet been performed.

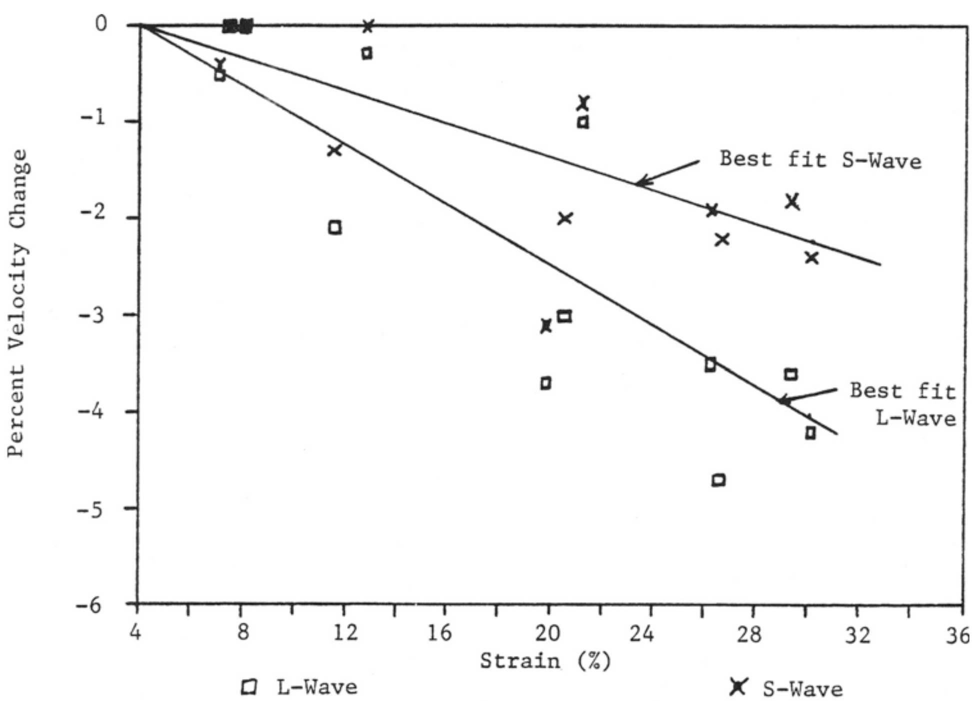

Fig. 5. Decrease in longitudinal- and shear-wave velocities with creep strain. The least squares best fit shows a greater decrease in L-wave velocity compared to S-wave velocity.

CONCLUSIONS

Ultrasonic velocity measurement methods were tested for their ability to detect creep damage. Tests showed that both L- and S-wave velocities decreased with strain produced by creep. The decrease in L-wave velocity was greater than the decrease in S-wave velocity. A decrease in surface- and creeping-wave velocity was also observed on creep samples.

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